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A User's Guide to the Zwikker-Kosten Transmission Line Code (ZKTL)

J. J. Kelly and H. Abu-Khajeel

December 1997

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A User's Guide to the Zwikker-Kosten Transmission Line Code (ZKTL)

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I. Abstract

This report documents updates to the Zwikker-Kosten Transmission Line Code (ZKTL) and serves as a users guide. The ZKTL software was developed for analyzing new liner technology, which has the goal of increasing the spectral range of sound absorption. Contiguous arrays of multi-degree-of-freedom (MDOF) liner elements serve as the model for these liner configurations, and Zwikker and Kosten's theory of sound propagation in channels is utilized to predict the surface impedance. Transmission matrices for the various liner elements are determined by both analytical and semi-empirical methods. This allows standard matrix techniques to be employed in the code to systematically calculate the composite impedance due to the individual liner elements. The ZKTL code consists of four independent subroutines. These four subroutines are:

1. Single channel impedance calculation - linear version (SCIC)
2. Single channel impedance calculation - nonlinear version (SCICNL)
3. Multi-channel, multi-segment, multi-layer impedance calculation - linear version (MCMSML)
4. Multi-channel, multi-segment, multi-layer impedance calculation - nonlinear version (MCMSMLNL)

Detailed examples, comments and explanations about executing all four modules for liner impedance computations are included in the report. Also contained in the guide are depictions of the interactive execution, input files and output files.

II. Introduction

The continuing need to improve suppression of turbomachinery noise in aircraft engine nacelles has led to consideration of new liner configurations that may allow for desired surface impedance distributions.[1] Conventional liners have typically been designed to attenuate discrete-frequency sound caused by the wakes of fan blades and outlet guide vanes.[2] Spectra associated with this noise mechanism are characterized by peaks at harmonics of the blade passage frequency (BPF). Thus, the sound field is essentially tonal and liner design strategies target specific frequencies for suppression. Abatement of discrete-frequency sound can be realized using a liner consisting of thin porous sheets bonded to honeycomb cores.[3,4] These types of liners are often referred to as lumped-element single-degree-of-freedom (SDOF) resonating systems. For these liner configurations, the acoustical resistance is due mainly to the porous sheets and the honeycomb core provides most of the acoustical reactance. Since the honeycomb cells do not interact with each other, these liners are classified as locally reacting. Although SDOF liners can be "tuned" to suppress relatively narrow band noise, they will not be adequate for broadband fan noise from future high-bypass-ratio engines or for tonal fan noise over a wide range of engine power settings.

A promising approach to enhanced broadband attenuation is the usage of liner configurations composed of continuous arrays of multi-degree-of-freedom (MDOF) liner elements. The computer code described in this document was developed for analyzing this new liner technology. Based on Zwikker and Kosten's theory for propagation of sound in channels,[5] the code predicts surface impedance and the sound absorption spectra for parallel element acoustical liners. Well-known matrix techniques are implemented in the computational scheme in order to systematically calculate the composite impedance due to the liner elements.

The Zwikker-Kosten Transmission Line Code (ZKTL) consists of four independent subroutines. These four subroutines are:

1. Single channel impedance calculation - linear version (SCIC)

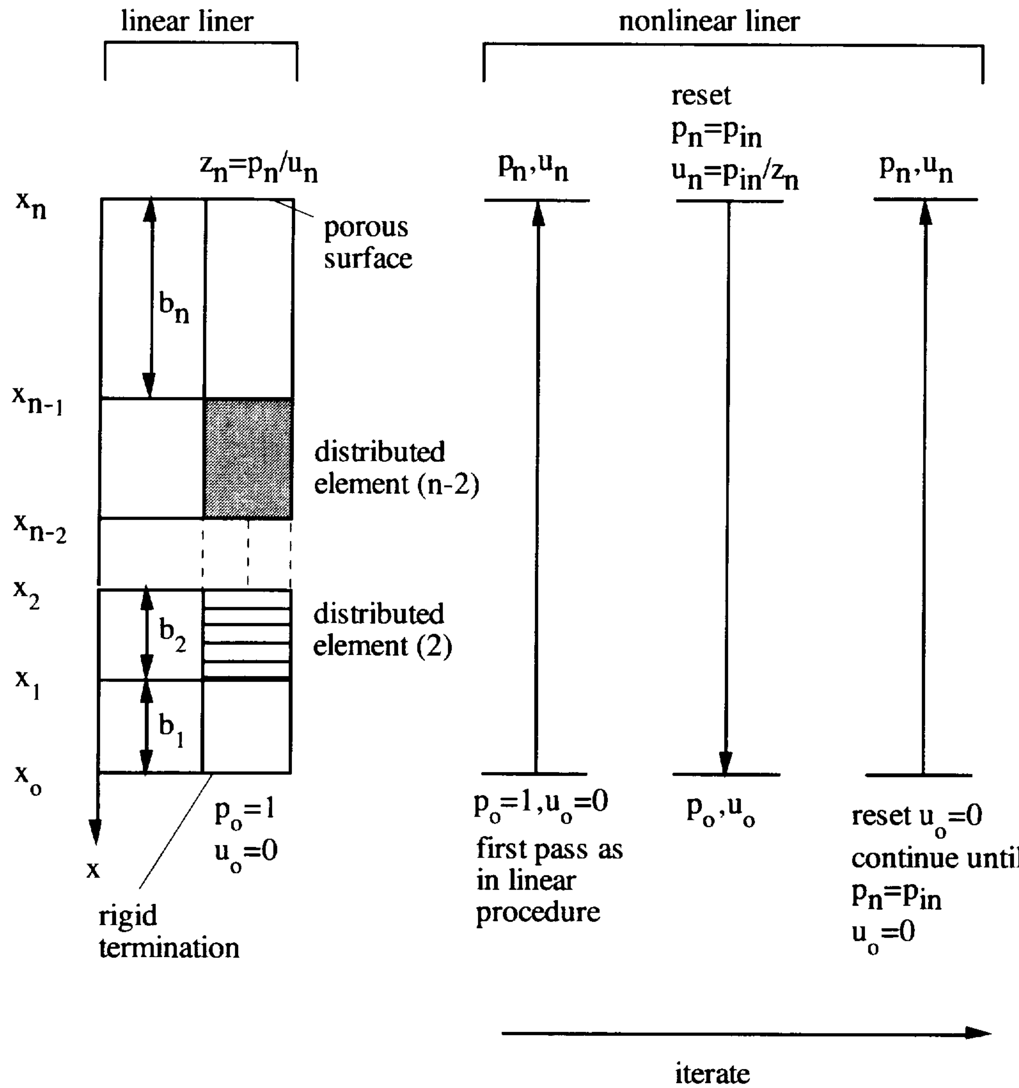
2. Single channel impedance calculation - nonlinear version (SCICNL)
3. Multi-channel, multi-segment, multi-layer impedance calculation - linear version (MCMSML)
4. Multi-channel, multi-segment, multi-layer impedance calculation - nonlinear version (MCMSMLNL)

The first two modules are for single channel calculations. The SCIC module is used to compute the surface impedance for a single channel using a linear assumption. This assumption implies that the impedance is independent of the incident sound pressure level (SPL) and the grazing mean flow velocity. The SCICNL module differs from SCIC in that the computed impedance is dependent on these two parameters. The latter two modules are for multiple parallel element liner configurations, one using the linear assumption and the other using the nonlinear assumption. All of the subroutines in the program contain comments about the model formulations and references. Segments are defined by their streamwise geometry at the outer rigid wall of the liner which is either uniform depth or varies in a linear manner. In the vertical dimension (normal to the liner surface), the liner can be layered; i.e. multi-degree of freedom (MDOF). The three options for each layer are open channel, foam channel (linear version only) and perforated sheet.

Figure 1 illustrates how the local surface impedance for a channel is determined by its constituent elements in series. Also, the linear and nonlinear computation schemes are depicted. For the linear procedure, the surface impedance is calculated by starting with the boundary condition at the termination of the channel, x_o , and marching to the liner surface. Transmission matrices for the various elements are determined by both analytical and semi-empirical methods. These matrices are then utilized to predict the surface impedance through a stepwise procedure starting at the bottom of the channel and culminating at the liner surface. The standard terminating condition for each channel is a rigid, impervious boundary which yields an infinite impedance. However, it should be noted that any desired impedance can be used as a terminating condition with a minor modification to the code.

An iteration scheme is employed in the nonlinear modules as shown in Fig. 1. The previously described linear procedure is implemented as the first pass in the iteration. Prior to the nonlinear pass going into the liner, +x direction, the computed acoustic pressure at the surface is modified to match the incident acoustic pressure (input). The acoustic particle velocity at the surface is then modified according to the incident pressure and the computed value of the surface impedance ($u_n=p_{in}/z_n$). After marching to the rigid wall, the acoustic particle velocity is modified to match the known condition ($u_o=0$). The iteration is continued until convergence is achieved ($p_n=p_{in}$, $u_o=0$), producing the required impedance.

Figure 1 Surface impedance computation schemes



III. SCIC

Figure 2 describes the input required for the SCIC module. For each option selected, the corresponding input queries are provided below the option in an indented format. The first layer, nearest the rigid termination, must be an open channel (true for all the modules). In Fig. 3 is a copy of the actual display prompts and input for a two layer case. Figure 4 shows the output file for this case. Relevant input parameters are included in the file, along with the normalized impedance, sound-pressure level difference (SPL) and phase difference between the bottom wall and surface at each frequency.

Figure 2 SCIC input

This option computes the normalized surface impedance of a single channel using linear acoustics

1. Global Parameters
    - Output Filename
    - Temperature
    - Channel Geometry
        - Tube .... Channel diameter
        - Slit .... Plate separation, Aspect ratio
    - Include absorption effects in characteristic impedance and propagation constant calculations?

2. Frequency Information
    - Lowest frequency of interest
    - Highest frequency of interest
    - Frequency step

3. Layer Information
    - Number of layers
    - Layer types (for each of the layers in the channel)
    - Open Channel
        - Channel length
    - Perforated Sheet, flow resistance is known
        - Flow resistance at 70 deg F
    - Perforated Sheet, A and B are known for the equation dp(f)= A(f)+iB(f)
        - Filename containing A, B as a function of layer and frequency
    - Foam
        - Flow resistance at 70 deg F
        - Foam thickness

Figure 3 SCIC interactive example

```
          MAIN MENU
 [1] Single Channel Impedance Calculation - Linear
 [2] Single Channel Impedance Calculation - Nonlinear
 [3] Multi-Channel, Multi-Segment, Multi-Layer Liner
 [4] Multi-Channel, Multi-Segment, Multi-Layer Nonlinear
     ENTER SELECTION [1-4, <=0 TO QUIT] :  1

     SCIC Routine
     ------------
        Input/Compute Global Parameters

Enter Output Filename : output.dat
Enter Temperature (deg C) :  23.0
Tube (1) or Slit (2) Geometry ? :  1
Include absorption effects in characteristic impedance
and propagation constant calculations? (0=Yes, 1=No) :  1
```

Input/Compute Frequency Information

Enter First Frequency (kHz) : 0.5
Enter Last Frequency (kHz) : 10.0
Enter Delta Frequency (kHz) : 0.1

Input/Compute Layer Information

NOTES :
1. One layer consists of one open channel, perforated sheet, or foam strip.
2. First layer is located at bottom of the liner, away from the surface.
3. Layer numbers increase toward the surface.
Enter # of layers : 2

Layer 1

1 = Open channel
2 = Perforated Sheet [Rf known]
3 = Perforated Sheet [dp(f)=A(f)+iB(f); A,B known]
4 = Foam
Enter choice : 1

Input/Compute Channel Information

Enter channel diameter (m) : 2.54000E-02
Enter length of channel (m) : 2.54000E-02

Layer 2

1 = Open channel
2 = Perforated Sheet [Rf known]
3 = Perforated Sheet [dp(f)=A(f)+iB(f); A,B known]
4 = Foam
Enter choice : 2

Input/Compute Channel Information

Enter channel diameter (m) : 2.54000E-02
Enter Flow Resistance (kg/m^2/s) at 70 deg F : 14.0

Figure 4 SCIC output file example

Output File is output.dat

Temperature (C)	0.230E+02
Density (kg/m^3)	0.119E+01
Sound Speed (m/s)	0.345E+03
Tube (1) or Slit (2) Geometry	1
Abs. Effects Included (0=Yes,1=No)	1
First Frequency (Hz)	0.500E+03

Last Frequency (Hz)	0.100E+05
Delta Frequency (Hz)	0.100E+03
Number of Frequencies	96

Layer 1

Channel Diameter (m)	0.2540E-01
Open channel length (m)	0.2540E-01

Layer 2

Channel Diameter (m)	0.2540E-01
Flow Resistance (kg/m^2/s)	0.139E+02

Delta Levels = Bottom Wall - Surface

Freq	Normalized Zeta		Delta dB	Delta deg
0.500	0.338E-01	-0.423E+01	0.234E+00	-0.458E+00
0.600	0.338E-01	-0.349E+01	0.338E+00	-0.554E+00
0.700	0.338E-01	-0.297E+01	0.462E+00	-0.652E+00
0.800	0.338E-01	-0.257E+01	0.607E+00	-0.754E+00
0.900	0.338E-01	-0.225E+01	0.773E+00	-0.859E+00
1.000	0.338E-01	-0.200E+01	0.962E+00	-0.968E+00

9.500	0.338E-01	-0.333E+00	0.996E+01	0.174E+03
9.600	0.338E-01	-0.282E+00	0.113E+02	0.173E+03
9.700	0.338E-01	-0.233E+00	0.128E+02	0.172E+03
9.800	0.338E-01	-0.185E+00	0.147E+02	0.170E+03
9.900	0.338E-01	-0.137E+00	0.171E+02	0.166E+03
10.000	0.338E-01	-0.905E-01	0.203E+02	0.160E+03

IV. SCICNL

In Fig. 5 is a depiction of the input logic for the SCICNL module. To be consistent, the linear coefficient, am, in the nonlinear equation for the impedance change across the sheet is calculated from the input flow resistance, Rfa, which is used for the linear pass. This is done in both SCICNL and MCMSMLNL by way of the following equation

$$am=Rfa/(\rho c)$$

where

$$\rho=\text{density}$$

$$c=\text{sound speed}$$

The above discussion applies to the option where the other sheet coefficients are input directly. For the option in which the coefficients are computed from additional input parameters, the code needs to be modified to calculate Rfa from am for consistency. In the current version of SCICNL, the software coding will give correct results if only two layers are considered in the case of inputting the sheet coefficients. If the coefficients are computed within the program, there is no problem with simulating multiple layers. It should perhaps be noted here that the MCMSMLNL module can compute the impedance for multiple layers for either options. Figure 6 shows the interactive execution of the subroutine using the same case as in Fig. 2 for the SCIC module. In this example, the sheet coefficients are entered directly. The input file containing the incident pressure signal as SPL vs. frequency is shown in Fig. 7. As can be seen from this example, the signal was input as a line spectrum. In this case, the spectrum is uniform at 125 dB and consists of 96 components with a spacing of 100 Hz and a passband of 500 Hz-10 kHz. Figure 8 contains the output file for this simulation with the computed nonlinear impedance.

Figure 5. SCICNL input

This option computes the normalized surface impedance of a single channel using nonlinear acoustics

1. Global Parameters
   - Output Filename
   - Input Filename
     - SPL vs Frequency at channel surface
   - Temperature
   - Bias flow velocity
   - Grazing flow velocity
   - Channel Geometry
   - Tube .... Channel diameter
   - Slit .... Plate separation
     Aspect ratio
   - Include absorption effects in characteristic impedance and propagation constant calculations?

2. Frequency Information
   - Lowest frequency of interest
   - Highest frequency of interest
   - Frequency step

3. Layer Information
   - Number of layers
   - Layer types (for each of the layers in the channel)_
     - Open channel
       - Channel length
     - Perforated Sheet
       - Flow resistance of sheet at 70 deg F
         - b,c,d for dz= a+b(u_a + u_b) +c*u_g + I d*f
           where u_a = normalized acoustic velocity
           u_b = normalized bias flow velocity
           u_g = normalized grazing flow velocity
           f = frequency
         - **** OR *****
         - Boundary layer displacement thickness
         - Sheet thickness
         - Orifice discharge coefficient
         - Sheet porosity
         - Orifice diameter

Figure 6. SCICNL interactive example

```
          MAIN MENU
 [1] Single Channel Impedance Calculation - Linear
 [2] Single Channel Impedance Calculation - Nonlinear
 [3] Multi-Channel, Multi-Segment, Multi-Layer Liner
 [4] Multi-Channel, Multi-Segment, Multi-Layer Nonlinear
     ENTER SELECTION [1-4, <=0 TO QUIT] : 2

     SCICNL Routine
     --------------
        Input/Compute Global Parameters
  Enter Output Filename : output.dat
  Enter Input Filename : input.dat
  Tube (1) or Slit (2) Geometry ? : 1

        Input/Compute Channel Information
  Enter channel diameter (m) : 2.54000E-02
  Enter Temperature (deg C) : 23.0
  Enter Bias Flow Velocity (m/s) : 0.0
  Enter Grazing Flow Velocity (m/s) : 0.0
  Include absorption effects in characteristic impedance
and propagation constant? (0=Yes, 1=No) : 1

        Input/Compute Frequency Information
  Enter First Frequency (kHz) : 0.5
  Enter Last Frequency (kHz)  : 10.0
  Enter Delta Frequency (kHz) : 0.1

        Input/Compute Layer Information

NOTES :
1. One layer consists of one open channel or perforated
   sheet.
2. First layer is located at bottom of the liner,
   away from the surface.
3. Layer numbers increase toward the surface.

It is assumed that the impedance change across
a perforated sheet is of the functional form
a+b*(u_a+u_b)+c*u_g + I*d*f
u_a, u_b and u_g are the normalized acoustic,
bias, and grazing velocities;
f is the frequency
   Enter coefficients (b,c,d) directly? (0=y, 1=n) : 0
   Enter # of layers : 2

   Layer 1

      1 = Open channel
      2 = Perforated Sheet
Enter choice : 1
   Enter length of channel (m) : 2.54000E-02
```

Layer 2

```
     1 = Open channel
     2 = Perforated Sheet
       Enter choice :  2
Enter Flow Resistance (kg/m^2/s) at 70 deg F :  14.0
 Enter b,c,d :  193.0, 0.0,0.0

    0 out of   96 frequencies converged
    5 out of   96 frequencies converged
   15 out of   96 frequencies converged
   15 out of   96 frequencies converged
   24 out of   96 frequencies converged
   29 out of   96 frequencies converged
   39 out of   96 frequencies converged
   45 out of   96 frequencies converged
   57 out of   96 frequencies converged
   72 out of   96 frequencies converged
   96 out of   96 frequencies converged
```

Figure 7. SCICNL input file example

```
  500.0 125
  600.0 125
  700.0 125
  800.0 125
  900.0 125
 1000.0 125
   -------
 9600.0 125
 9700.0 125
 9800.0 125
 9900.0 125
10000.0 125
```

Figure 8. SCICNL output file example

```
Output File is      output.dat
Tube (1) or Slit (2) Geometry                   1
Channel Diameter (m)                   0.2540E-01
Temperature (C)                         0.230E+02
Density (kg/m^3)                        0.119E+01
Sound Speed (m/s)                       0.345E+03

Bias Flow Velocity (m/s)                0.000E+00
Grazing Flow Velocity (m/s)             0.000E+00
Abs. Effects Included (0=Yes,1=No)              1

First Frequency (Hz)                    0.500E+03
Last Frequency (Hz)                     0.100E+05
Delta Frequency (Hz)                    0.100E+03
```

Number of Frequencies 96

Layer 1
Open channel length (m) 0.2540E-01

Layer 2
Flow Resistance (kg/m^2/s) 0.139E+02
a = 0.3378E-01,b = 0.1930E+03,c = 0.0000E+00,d = 0.0000E+00

Freq		Normalized Zeta	
kHz	SPL	Real	Imag
0.500E+00	0.125E+03	0.541E+00	-0.423E+01
0.600E+00	0.125E+03	0.541E+00	-0.349E+01
0.700E+00	0.125E+03	0.541E+00	-0.297E+01
0.800E+00	0.125E+03	0.541E+00	-0.257E+01
0.900E+00	0.125E+03	0.541E+00	-0.225E+01
0.100E+01	0.125E+03	0.541E+00	-0.200E+01

0.950E+01	0.125E+03	0.541E+00	-0.333E+00
0.960E+01	0.125E+03	0.541E+00	-0.282E+00
0.970E+01	0.125E+03	0.541E+00	-0.233E+00
0.980E+01	0.125E+03	0.541E+00	-0.185E+00
0.990E+01	0.125E+03	0.541E+00	-0.137E+00
0.100E+02	0.125E+03	0.541E+00	-0.905E-01

V. MCMSML

Figure 9 illustrates the input logic for the MCMSML module. In Fig. 10, the execution prompts for a particular example are shown. This case is a two-layer, two-segment liner, and a geometrical description is shown in Fig. 11. Note that each segment has a unique uniform depth. The output file for this example is displayed in Fig. 12.

Figure 9. MCMSML input

This option computes the normalized surface impedance of an entire liner consisting of a number of channels, segments and/or layers using linear acoustics

1. Global Parameters
   Output Filename
   Temperature
   Channel Geometry
      Tube .... Channel diameter
      Slit .... Plate separation
                     Total number of slits
   Include absorption effects in characteristic impedance and propagation constant calculations?
   Liner streamwise length
   Liner spanwise width
   Flow Mach number
   Angle of incidence (re normal incidence)

2. Frequency Information
   Lowest frequency of interest

Highest frequency of interest
Frequency step

3. Segment Information
   Total number of segments
   Segment streamwise length
   3.1 Layer information
     Number of layers in segment
     Layer types (for each of the layers in the channel)
       Open Channel
         Channel length
         One layer
           Open channel layer type
             Linear slopes
             Quadratic residue
               Odd prime for Sn
               Maximum channel length
         More than one layer
           Length of channel at x=min
           Length of channel at x=max
     Perforated Sheet, flow resistance is known
       Flow resistance at 70 deg F
     Perforated Sheet, A and B are known for the equation dp(f)= A(f)+iB(f)
       Filename containing A, B as a function of layer and frequency
     Foam
       Flow resistance at 70 deg F
       Foam thickness

Figure 10. MCMSML interactive example

```
         MAIN MENU
 [1] Single Channel Impedance Calculation - Linear
 [2] Single Channel Impedance Calculation - Nonlinear
 [3] Multi-Channel, Multi-Segment, Multi-Layer Liner
 [4] Multi-Channel, Multi-Segment, Multi-Layer Nonlinear
     ENTER SELECTION [1-4, <=0 TO QUIT] :  3

     MCMSML Routine
     --------------
        Input/Compute Global Parameters

Enter Output Filename : output.dat

Enter Temperature (deg C) :  20.0
Tube (1) or Slit (2) Geometry ? :  2
Include absorption effects in characteristic impedance
and propagation constant? (0=Yes, 1=No) :  0

        Input/Compute Geometry Information

Enter liner streamwise length (m) :  0.4063999
Enter liner spanwise width (m) :  5.08000E-02
```

Input/Compute Channel Information
Enter plate separation (m) : 5.50000E-03
Enter total # slits : 65

Input/Compute Frequency Information

Enter First Frequency (kHz) : 0.5
Enter Last Frequency (kHz) : 3.0
Enter Delta Frequency (kHz) : 0.1

Input/Compute M and Theta Information

Enter Flow Mach Number : 0.0
Enter Angle of Incidence (re Normal, deg) : 0.0

Input/Compute Segment/Layer Information

NOTES :
1. One segment consists of a group of vertical layers, each of which has a specified length and slope.
2. One layer consists of one open channel, perforated sheet, or foam strip.
3. First layer is located at bottom of the liner, away from the surface.
4. Layer numbers increase toward the surface.

Enter total # of segments : 2

Segment 1
Enter segment streamwise length (m) : 0.2031999
Enter # of layers in segment 1 : 2

Layer 1

1 = Open channel
2 = Perforated Sheet [Rf known]
3 = Perforated Sheet [dp(f)=A(f)+iB(f); A,B known]
4 = Foam
Enter choice : 1

Linear Slopes (1) or Quadratic Residue (2) : 1

Enter length (m) of channel at x = min : 5.74000E-02
Enter length (m) of channel at x = max : 5.74000E-02

Layer 2

1 = Open channel
2 = Perforated Sheet [Rf known]
3 = Perforated Sheet [dp(f)=A(f)+iB(f); A,B known]
4 = Foam
Enter choice : 2

Enter Flow Resistance (kg/m^2/s) at 70 deg F : 14.0

Segment 2
Segment streamwise length (m) is 0.2032E+00
Enter # of layers in segment 2 : 2

Layer 1

1 = Open channel
2 = Perforated Sheet [Rf known]
3 = Perforated Sheet [dp(f)=A(f)+iB(f); A,B known]
4 = Foam
Enter choice : 1

Linear Slopes (1) or Quadratic Residue (2) : 1

Enter length (m) of channel at x = min : 2.87000E-02
Enter length (m) of channel at x = max : 2.87000E-02

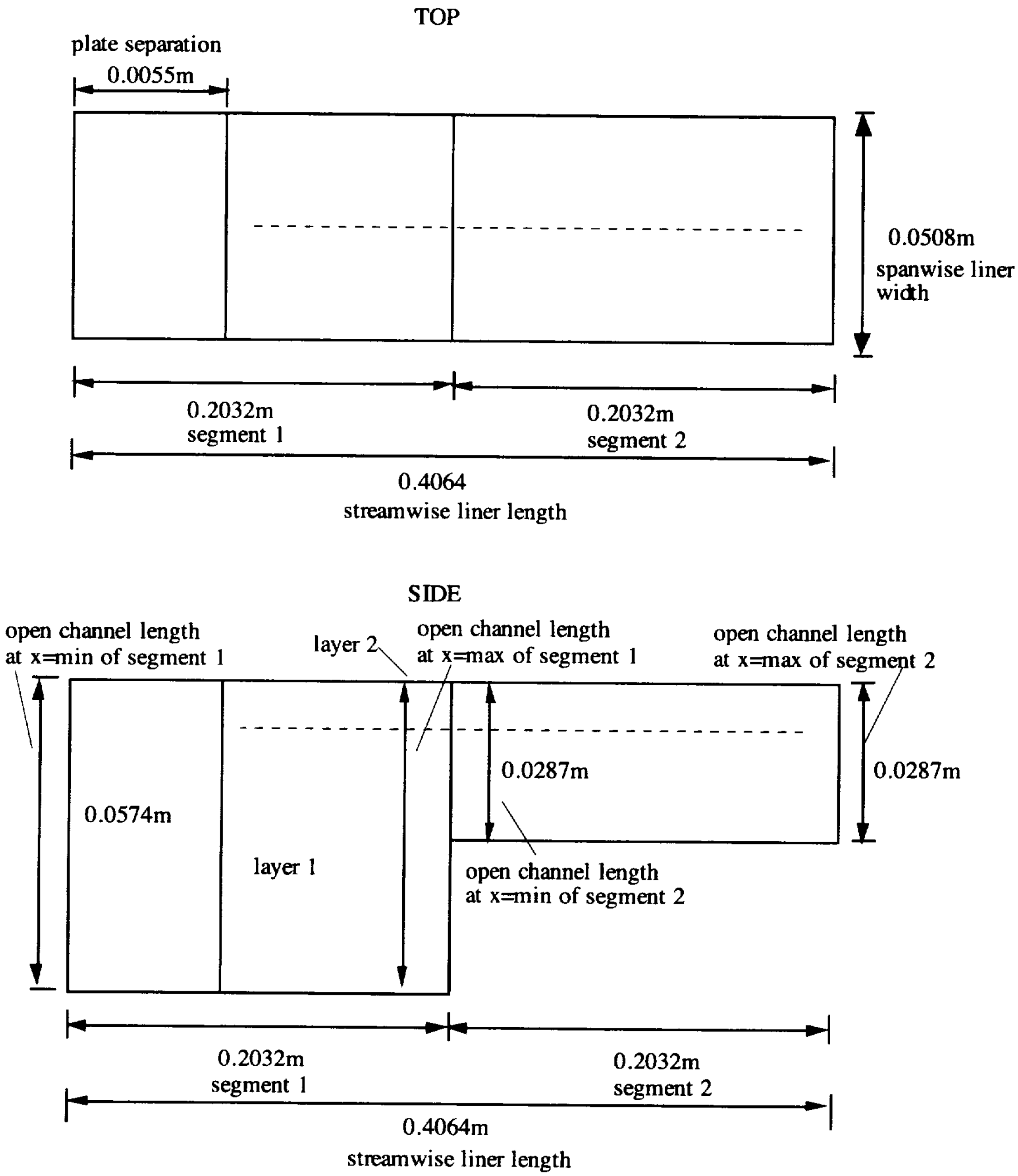
Layer 2

1 = Open channel
2 = Perforated Sheet [Rf known]
3 = Perforated Sheet [dp(f)=A(f)+iB(f); A,B known]
4 = Foam

Enter choice : 2

Enter Flow Resistance (kg/m^2/s) at 70 deg F : 14.0

Figure 11. Liner geometry



2 Segments

Figure 12. MCMSML output file example

Output File is output.dat

Temperature (C)	0.200E+02
Density (kg/m^3)	0.120E+01
Sound Speed (m/s)	0.344E+03
Tube (1) or Slit (2) Geometry	2
Abs. Effects Included (0=Yes,1=No)	0
Streamwise Liner Length (m)	0.4064E+00
Spanwise Liner Width (m)	0.5080E-01
Plate Separation (m)	0.5500E-02
Aspect Ratio	0.9236E+01
No. Slits	65
First Frequency (Hz)	0.500E+03
Last Frequency (Hz)	0.300E+04
Delta Frequency (Hz)	0.100E+03
Number of Frequencies	26
Flow Mach Number	0.000E+00
Angle of Incidence (deg)	0.000E+00
Flow Resistance (kg/m^2/s)	0.141E+02
Flow Resistance (kg/m^2/s)	0.141E+02
Segment 1 Layer 1	
Open channel length (m) at x = min	0.5740E-01
Open channel length (m) at x = max	0.5740E-01
Segment 1 Layer 2	
Flow Resistance (kg/m^2/s)	0.141E+02
Segment 2 Layer 1	
Open channel length (m) at x = min	0.2870E-01
Open channel length (m) at x = max	0.2870E-01
Segment 2 Layer 2	
Flow Resistance (kg/m^2/s)	0.141E+02

Freq kHz	Normalized Zeta		A.C.	R.F.	I.L. dB
0.500	0.509E+00	-0.267E+01	0.22	0.78	-1.06
0.600	0.455E+00	-0.215E+01	0.27	0.73	-1.37
0.700	0.424E+00	-0.176E+01	0.33	0.67	-1.75
0.800	0.399E+00	-0.146E+01	0.39	0.61	-2.16
0.900	0.395E+00	-0.120E+01	0.47	0.53	-2.72
1.000	0.398E+00	-0.983E+00	0.54	0.46	-3.42

2.600	0.624E+00	-0.391E+00	0.89	0.11	-9.76
2.700	0.586E+00	-0.284E+00	0.90	0.10	-10.14
2.800	0.569E+00	-0.181E+00	0.91	0.09	-10.59

2.900	0.572E+00	-0.759E-01	0.92	0.08	-11.18
3.000	0.579E+00	0.425E-01	0.93	0.07	-11.43

VI. MCMSMLNL

The input logic for this module is depicted in Fig. 13. For the input, the flow Mach number and grazing flow velocity (m/s) must be equivalent. To simulate a duct or inlet, the angle of incidence must be zero. If this is the case, the flow Mach number is irrelevant since it is not used in the calculation of the impedance. To consider a quiescent situation, where the grazing flow velocity is zero, the bias flow velocity must also be zero. Execution of the subroutine is illustrated in Fig. 14. This example uses the same input as that shown in Fig. 10 for the linear module. The main difference for this module is that now a SPL vs. frequency file is required input. Refer to Fig. 11 for a geometrical description of the example. Figure 15 contains the input file that was used for this simulation. As can be seen from the input file, the spectrum consists of 26 discrete tones, ranging from 500 Hz to 3 kHz at 100 Hz intervals, which was the same spectral content as was used for the MCMSML example. For both segments, a uniform pressure field of 130 dB is incident which has an OASPL of 144 dB. The pressure signal can vary spectrally within each segment but must be spatially uniform for each segment. Also, the spectral lines have to be the same across all segments, although the pressure levels can vary. Finally, Fig. 16 shows the output file for this example. Notice the difference in impedance, especially in the resistivity, between this example and that of Fig. 12 for a linear simulation. This is due to the liner nonlinearity. However, as the incident pressure is decreased in amplitude, the results of MCMSMLNL correctly approach those of MCMSML.

Figure 13. MCMSMLNL input

This option computes the normalized surface impedance of an entire liner consisting of a number of channels, segments and/or layers using nonlinear acoustics

1. Global Parameters
   - <u>Output Filename</u>
   - <u>Input Filename</u>
     - <u>SPL vs Frequency at channel surface for each segment</u>
   - <u>Temperature</u>
   - <u>Bias flow velocity</u>
   - <u>Grazing flow velocity</u>
   - <u>Channel Geometry</u>
     - <u>Tube</u> .... <u>Channel diameter</u>, <u>Number of channels per square meter</u>
     - <u>Slit</u> .... <u>Plate separation</u>, <u>Total number of slits</u>
   - <u>Include absorption effects in characteristic impedance and propagation constant calculations?</u>
   - <u>Liner streamwise length</u>
   - <u>Liner spanwise width</u>
   - <u>Flow Mach number</u>
   - <u>Angle of incidence</u> (re normal incidence)

2. Frequency Information
   - <u>Lowest frequency of interest</u>
   - <u>Highest frequency of interest</u>

Frequency step

3. Segment Information
Total number of segments
Segment streamwise length
3.1 Layer information
Number of layers in segment
Layer types (for each of the layers in the channel)
Open Channel
Channel length
One layer
Open channel layer type
Linear slopes
Quadratic residue
Odd prime for Sn
Maximum channel length
More than one layer
Length of channel at x=min
Length of channel at x=max
Perforated Sheet
Flow resistance of sheet at 70 deg F
b,c,d for dz= a+b(u_a + u_b) +c*u_g + I d*f
where u_a = normalized acoustic velocity
u_b = normalized bias flow velocity
u_g = normalized grazing flow velocity
f = frequency
**** OR *****
Boundary layer displacement thickness
Sheet thickness
Orifice discharge coefficient
Sheet porosity
Orifice diameter

Figure 14. MCMSMLNL interactive example

MAIN MENU
[1] Single Channel Impedance Calculation - Linear
[2] Single Channel Impedance Calculation - Nonlinear
[3] Multi-Channel, Multi-Segment, Multi-Layer Liner
[4] Multi-Channel, Multi-Segment, Multi-Layer Nonlinear
ENTER SELECTION [1-4, <=0 TO QUIT] : 4

MCMSMNL Routine

Input/Compute Global Parameters

Enter Output Filename : output.dat
Enter Input Filename : input.dat

Enter Temperature (deg C) : 20.0
Tube (1) or Slit (2) Geometry ? : 2
Include absorption effects in characteristic impedance
and propagation constant? (0=Yes, 1=No) : 0

It is assumed that the impedance change across
a perforated sheet is of the functional form
a+b*(u_a+u_b)+c*u_g + I*d*f
u_a, u_b and u_g are the normalized acoustic,
bias, and grazing velocities;
f is the frequency
  Enter coefficients (a,b,c,d) directly? (0=y, 1=n) : 0

Input/Compute Geometry Information

Enter liner streamwise length (m) : 0.4063999
Enter liner spanwise width (m) : 5.08000E-02

Input/Compute Channel Information
Enter plate separation (m) : 5.50000E-03
Enter total # slits : 65

Input/Compute Frequency Information

Enter First Frequency (kHz) : 0.5
Enter Last Frequency (kHz) : 3.0
Enter Delta Frequency (kHz) : 0.1

Input/Compute M and Theta Information

Enter Flow Mach Number : 0.0
Enter Bias Flow Velocity (m/s) : 0.0
Enter Angle of Incidence (re Normal, deg) : 0.0

Input/Compute Segment/Layer Information

NOTES :
1. One segment consists of a group of vertical layers,
   each of which has a specified length and slope.
2. One layer consists of one open channel, perforated
   sheet, or foam strip.
3. First layer is located at bottom of the liner,
   away from the surface.
4. Layer numbers increase toward the surface.

Enter total # of segments : 2

Segment 1
  Enter segment streamwise length (m) : 0.2031999
  Enter # of layers in segment 1 : 2

  Layer 1

    1 = Open channel
    2 = Perforated Sheet [Rf known]
      Enter choice : 1

      Linear Slopes (1) or Quadratic Residue (2) : 1

```
      Enter length (m) of channel at x = min :  5.74000E-02
      Enter length (m) of channel at x = max :  5.74000E-02

  Layer 2

    1 = Open channel
    2 = Perforated Sheet [Rf known]
      Enter choice :  2

       Enter Flow Resistance (kg/m^2/s) at 70 deg F :  14.0
  Enter b,c,d :  193.0, 0.0,0.0

 Segment  2
  Segment streamwise length (m) is  0.2032E+00
  Enter # of layers in segment  2 :  2

  Layer 1

    1 = Open channel
    2 = Perforated Sheet [Rf known]
      Enter choice :  1

      Linear Slopes (1) or Quadratic Residue (2) :  1

      Enter length (m) of channel at x = min :  2.87000E-02
      Enter length (m) of channel at x = max :  2.87000E-02

Layer 2

    1 = Open channel
    2 = Perforated Sheet [Rf known]
      Enter choice :  2

       Enter Flow Resistance (kg/m^2/s) at 70 deg F :  14.0
  Enter b,c,d :  193.0,0.0,0.0
```

Figure 15. MCMSMLNL input file example

```
 500.0 130 130
 600.0 130 130
 700.0 130 130
 800.0 130 130
 900.0 130 130
1000.0 130 130
   ------------
2500.0 130 130
2600.0 130 130
2700.0 130 130
2800.0 130 130
2900.0 130 130
3000.0 130 130
```

Figure 16. MCMSMLNL output file example

```
Output File is      output.dat

Temperature (C)                        0.200E+02
Density (kg/m^3)                       0.120E+01
Sound Speed (m/s)                      0.344E+03

Tube (1) or Slit (2) Geometry                  2
Abs. Effects Included (0=Yes,1=No)             0

Streamwise Liner Length (m)           0.4064E+00
Spanwise Liner Width (m)              0.5080E-01
Plate Separation (m)                  0.5500E-02
Aspect Ratio                          0.9236E+01
No. Slits                                     65

First Frequency (Hz)                   0.500E+03
Last Frequency (Hz)                    0.300E+04
Delta Frequency (Hz)                   0.100E+03
Number of Frequencies                         26

Flow Mach Number                       0.000E+00
Bias Flow Velocity (m/s)               0.000E+00
Grazing Flow Velocity (m/s)            0.000E+00
Angle of Incidence (deg)               0.000E+00

    layer Property for segment    1
     layer                   2
Flow Resistance (kg/m^2/s)        0.141E+02
 a =  0.3395E-01,b =  0.1930E+03,c =  0.0000E+00,d =  0.0000E+00

    layer Property for segment    2
     layer                   2
Flow Resistance (kg/m^2/s)        0.141E+02
 a =  0.3395E-01,b =  0.1930E+03,c =  0.0000E+00,d =  0.0000E+00


    Segment  1 Layer  1
Open channel length (m) at x = min  0.5740E-01
Open channel length (m) at x = max  0.5740E-01

    Segment  1 Layer  2
Flow Resistance (kg/m^2/s)        0.141E+02

    Segment  2 Layer  1
Open channel length (m) at x = min  0.2870E-01
Open channel length (m) at x = max  0.2870E-01

    Segment  2 Layer  2
Flow Resistance (kg/m^2/s)        0.141E+02
```

Freq	Normalized Zeta	
kHz	Real	Imag
0.500	0.367E+01	-0.286E+01
0.600	0.359E+01	-0.235E+01
0.700	0.353E+01	-0.197E+01
0.800	0.348E+01	-0.168E+01
0.900	0.346E+01	-0.144E+01
1.000	0.344E+01	-0.124E+01

2.500	0.395E+01	0.655E+00
2.600	0.422E+01	0.773E+00
2.700	0.464E+01	0.812E+00
2.800	0.529E+01	0.628E+00
2.900	0.618E+01	0.120E+00
3.000	0.644E+01	-0.176E-01

VII. Future Plans

It should be noted that the ZKTL code is continually evolving. As innovative derivations become available for additional layer types, they will be incorporated into ZKTL. Similarly, the current modules will be continually upgraded to incorporate improved understanding of the underlying physics. In the near term, the nonlinear modules will be upgraded for improved accuracy in the simulation of broadband noise.

VIII. References

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13. ABSTRACT (Maximum 200 words)

This user's guide documents updates to the Zwikker-Kosten Transmission Line Code (ZKTL). This code was developed for analyzing new liner concepts developed to provide increased sound absorption. Contiguous arrays of multi-degree-of-freedom (MDOF) liner elements serve as the model for these liner configurations, and Zwikker and Kosten's theory of sound propagation in channels is used to predict the surface impedance. Transmission matrices for the various liner elements incorporate both analytical and semi-empirical methods. This allows standard matrix techniques to be employed in the code to systematically calculate the composite impedance due to the individual liner elements. The ZKTL code consists of four independent subroutines:

1. Single channel impedance calculation — linear version (SCIC)
2. Single channel impedance calculation — nonlinear version (SCICNL)
3. Multi-channel, multi-segment, multi-layer impedance calculation — linear version (MCMSML)
4. Multi-channel, multi-segment, multi-layer impedance calculation — nonlinear version (MCMSMLNL)

Detailed examples, comments, and explanations for each liner impedance computation module are included. Also contained in the guide are depictions of the interactive execution, input files and output files.

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